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PATENT APPLICATION

IONICALLY CONDUCTIVE MEMBRANES FOR PROTECTION OF ACTIVE METAL ANODES AND BATTERY CELLS

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Ionically Conductive Membranes for Protection of Active Metal Anodes and Battery Cells

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Patent Application No. 10/731,771 filed December 5, 2003, titled Ionically Conductive Composites for Protection of Active Metal Anodes, which is a continuation-in-part of U.S. Patent Application No. 10/686,189 filed October 14, 2003, titled Ionically Conductive Composites for Protection of Active Metal Anodes, which claims priority to U.S. Provisional Patent Application No. 60/418,899 filed October 15, 2002, titled Ionically Conductive Composites for Protection of Anodes and Electrolytes.

This application also claims priority to U.S. Provisional Patent Application No. 60/511,710 filed October 14, 2003, titled IONICALLY CONDUCTIVE COMPOSITES FOR PROTECTION OF ACTIVE METAL ELECTRODES IN CORROSIVE ENVIRONMENTS and U.S. Provisional Patent Application No. 60/518,948 filed November 10, 2003, titled BI-FUNCTINALLY COMPATIBLE IONICALLY COMPOSITES FOR ISOLATION OF ACTIVE METAL ELECTRODES IN A VARIETY OF ELECTROCHEMICAL CELLS AND SYSTEMS.

Each of these prior applications is incorporated herein by reference in its entirety and for all purposes.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to separators and electrode structures for use in batteries. More particularly, this invention relates to ionically conductive membranes for protection of active metal anodes from deleterious reaction with air, moisture and other battery components, battery cells incorporating such protected anodes and methods for their fabrication.

2. Description of Related Art

The low equivalent weight of alkali metals, such as lithium, render them particularly attractive as a battery electrode component. Lithium provides greater energy per volume than the traditional battery standards, nickel and cadmium. Unfortunately, no rechargeable lithium metal batteries have yet succeeded in the market place.

The failure of rechargeable lithium metal batteries is largely due to cell cycling problems. On repeated charge and discharge cycles, lithium "dendrites" gradually grow out from the lithium metal electrode, through the electrolyte, and ultimately contact the positive electrode. This causes an internal short circuit in the battery, rendering the battery unusable after a relatively few cycles. While cycling, lithium electrodes may also grow "mossy" deposits which can dislodge from the negative electrode and thereby reduce the battery's capacity.

To address lithium's poor cycling behavior in liquid electrolyte systems, some researchers have proposed coating the electrolyte facing side of the lithium negative electrode with a "protective layer." Such protective layer must conduct lithium ions, but at the same time prevent contact between the lithium electrode surface and the bulk electrolyte. Many techniques for applying protective layers have not succeeded.

Some contemplated lithium metal protective layers are formed *in situ* by reaction between lithium metal and compounds in the cell's electrolyte which contact the lithium. Most of these *in situ* films are grown by a controlled chemical reaction after the battery is assembled. Generally, such films have a porous morphology allowing some electrolyte to penetrate to the bare lithium metal surface. Thus, they fail to adequately protect the lithium electrode.

Various pre-formed lithium protective layers have been contemplated. For example, US Patent No. 5,314,765 (issued to Bates on May 24, 1994) describes an *ex situ* technique for fabricating a lithium electrode containing a thin layer of sputtered lithium phosphorus oxynitride ("LiPON") or related material. LiPON is a glassy single ion conductor (conducts lithium ion) which has been studied as a potential electrolyte for solid state lithium microbatteries that are fabricated on silicon and used to power integrated circuits (See US Patents Nos. 5,597,660, 5,567,210, 5,338,625, and 5,512,147, all issued to Bates et al.).

Work in the present applicants' laboratories has developed technology for the use of glassy or amorphous protective layers, such as LiPON, in active metal battery electrodes. (See, for example, US Patents 6,025,094, issued 02/15/00, 6,402,795, issued 06/11/02, 6,214,061, issued 04/10/01 and 6,413,284, issued 07/02/02, all assigned to PolyPlus Battery Company). Despite this progress, alternative protective layers and structures that could also enhance active metal, particularly lithium metal, battery performance continue to be sought. In particular, protective layers that combine the characteristics of high ionic conductivity and chemical stability to materials and conditions on either side of the protective layer are desired.

SUMMARY OF THE INVENTION

The present invention provides ionically conductive membranes for decoupling the active metal anode and cathode sides of an active metal electrochemical cell, and methods for their fabrication. The membranes may be incorporated in active metal negative electrode (anode) structures and electrochemical devices and components, including battery and fuel cells. The membranes are highly conductive for ions of the active metal, but are otherwise substantially impervious. They are chemically stable on one side to the active metal of the anode (e.g., lithium), and on the other side to the cathode, other battery cell components such as solid or liquid phase electrolytes, including organic or aqueous liquid electrolytes, ambient conditions and other environments corrosive to the active metal of the anode if directly contacted with it. The membrane is capable of protecting an active metal anode from deleterious reaction with other battery components or ambient conditions and decoupling the chemical environments of the anode and cathode enabling use of anode-incompatible materials, such as solvents and electrolytes, on the cathode side without deleterious impact on the anode, and vice versa. This broadens the array of materials that may be used in active metal electrochemical cells and facilitates cell fabrication while providing a high level of ionic conductivity to enhance performance of an electrochemical cell in which the membrane is incorporated.

The membrane may have any suitable composition, for example, it may be a monolithic material chemically compatible with both the anode and cathode environments, or a composite composed of at least two components of different materials having different chemical compatibilities, one chemically compatible with the anode environment and the other chemically compatible with the cathode environment.

Composite membranes may be composed of a laminate of discrete layers of materials having different chemical compatibility requirements, or it may be composed of a gradual transition between layers of the materials. By "chemical compatibility" (or "chemically compatible") it is meant that the referenced material does not react to form a product that is deleterious to battery cell operation when contacted with one or more other referenced battery cell components or manufacturing, handling or storage conditions. A first material layer (or first layer material) of the composite is ionically conductive, and chemically compatible with an active metal electrode material. Chemical compatibility in this aspect of the invention refers both to a material that is chemically stable and therefore substantially unreactive when contacted with an active metal electrode material. It may also refer to a material that is chemically stable with air, to facilitate storage and handling, and reactive when contacted with an active metal electrode material to produce a product that is chemically stable against the active metal electrode material and has the desirable ionic conductivity (i.e., a first layer material). Such a reactive material is sometimes referred to as a "precursor" material. A second material layer of the composite is substantially impervious, ionically conductive and chemically compatible with the first material. Additional layers are possible to achieve these aims, or otherwise enhance electrode stability or performance. All layers of the composite have high ionic conductivity, at least 10^{-7}S/cm, generally at least 10^{-6}S/cm, for example at least 10^{-5}S/cm to 10^{-4}S/cm, and as high as 10^{-3}S/cm or higher so that the overall ionic conductivity of the multi-layer protective structure is at least 10^{-7}S/cm and as high as 10^{-3}S/cm or higher.

A wide variety of materials may be used in fabricating protective composites in accordance with the present invention, consistent with the principles described above. For example, the first layer, in contact with the active metal, may be composed, in whole or in part, of active metal nitrides, active metal phosphides, active metal halides or active metal phosphorus oxynitride-based glass. Specific examples include Li_3N, Li_3P, LiI, LiBr, LiCl, LiF and LiPON. Active metal electrode materials (e.g., lithium) may be applied to these materials, or they may be formed *in situ* by contacting precursors such as metal nitrides, metal phosphides, metal halides, red phosphorus, iodine, nitrogen or phosphorus containing organics and polymers, and the like with lithium. The *in situ* formation of the first layer may result from an incomplete conversion of the precursors to their lithiated analog. Nevertheless, such incomplete conversions meet the requirements of a first layer material for a protective composite in accordance with the present invention and are therefore within the scope of the invention.

A second layer of the protective composite may be composed of a material that is substantially impervious, ionically conductive and chemically compatible with the first material or precursor and environments normally corrosive to the active metal of the anode, including glassy or amorphous metal ion conductors, such as a phosphorus-based glass, oxide-based glass, phosphorus-oxynitride-based glass, sulpher-based glass, oxide/sulfide based glass, selenide based glass, gallium based glass, germanium-based glass or boracite glass (such as are described D.P. Button et al., Solid State Ionics, Vols. 9-10, Part 1, 585-592 (December 1983); ceramic active metal ion conductors, such as lithium beta-alumina, sodium beta-alumina, Li superionic conductor (LISICON), Na superionic conductor (NASICON), and the like; or glass-ceramic active metal ion conductors. Specific examples include LiPON, $Li_3PO_4.Li_2S.SiS_2$, $Li_2S.GeS_2.Ga_2S_3$, $Li_2O\cdot 11Al_2O_3$, $Na_2O\cdot 11Al_2O_3$, $(Na, Li)_{1+x}Ti_{2-x}Al_x(PO_4)_3$ ($0.6\leq x\leq 0.9$) and crystallographically related structures, $Na_3Zr_2Si_2PO_{12}$, $Li_3Zr_2Si_2PO_{12}$, $Na_5ZrP_3O_{12}$, $Na_5TiP_3O_{12}$, $Na_3Fe_2P_3O_{12}$, $Na_4NbP_3O_{12}$, $Li_5ZrP_3O_{12}$, $Li_5TiP_3O_{12}$, $Li_3Fe_2P_3O_{12}$ and $Li_4NbP_3O_{12}$, and combinations thereof, optionally sintered or melted. Suitable ceramic ion active metal ion conductors are described, for example, in US Patent No. 4,985,317 to Adachi *et al.*, incorporated by reference herein in its entirety and for all purposes.

A particularly suitable glass-ceramic material for the second layer of the protective composite is a lithium ion conductive glass-ceramic having the following composition:

Composition	mol %
P_2O_5	26-55%
SiO_2	0-15%
$GeO_2 + TiO_2$	25-50%
in which GeO_2	0--50%
TiO_2	0--50%
ZrO_2	0-10%
M_2O_3	0 < 10%
Al_2O_3	0-15%

Ga_2O_3	0-15%
Li_2O	3-25%

and containing a predominant crystalline phase composed of $Li_{1+x}(M,Al,Ga)_x(Ge_{1-y}Ti_y)_{2-x}(PO_4)_3$ where $X\leq 0.8$ and $0\leq Y\leq 1.0$, and where M is an element selected from the group consisting of Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb and/or and $Li_{1+x+y}Q_xTi_{2-x}Si_yP_{3-y}O_{12}$ where $0< X\leq 0.4$ and $0< Y\leq 0.6$, and where Q is Al or Ga. The glass-ceramics are obtained by melting raw materials to a melt, casting the melt to a glass and subjecting the glass to a heat treatment. Such materials are available from OHARA Corporation, Japan and are further described in US Patent Nos. 5,702,995, 6,030,909, 6,315,881 and 6,485,622, incorporated herein by reference.

Either layer may also include additional components. For instance, a suitable active metal compatible layer (first layer) may include a polymer component to enhance its properties. For example, polymer-iodine complexes like poly(2-vinylpyridine)-iodine (P2VP-I_2), polyethylene-iodine, or tetraalkylammonium-iodine complexes can react with Li to form a LiI-based film having significantly higher ionic conductivity than that for pure LiI. Also, a suitable first layer may include a material used to facilitate its use, for example, the residue of a wetting layer (e.g., Ag) used to prevent reaction between vapor phase lithium (during deposition) and LiPON when LiPON is used as a first layer material.

In solid state embodiments, a suitable second layer may include a polymer component to enhance its properties. For example, a glass-ceramic active metal ion conductor, like the glass-ceramic materials described above, may also be combined with polymer electrolytes to form flexible composite sheets of material which may be used as second layer of the protective composite. One important example of such a flexible composite material has been developed by OHARA Corp. (Japan). It is composed of particles of a Li-ion conducting glass-ceramic material, such as described above, and a solid polymer electrolyte based on PEO-Li salt complexes. OHARA Corp. manufactures this material in the form of sheet with a thickness of about 50 microns that renders it flexible while maintaining its high ionic conductivity. Because of its relatively high ionic conductivity (better than $4*10^{-5}$ S/cm at room temperature in the case of the OHARA product) and stability toward metallic Li, this type of composite electrolyte can be used at room temperature or elevated temperatures in fully solid-state cells.

In addition, the layers may be formed using a variety of techniques. These include deposition or evaporation (including e-beam evaporation) of layers of material, such as Li_3N or an ionically conductive glass. Also, as noted above, the active metal electrode adjacent layer may be formed *in situ* from the non-deleterious reaction of one or more precursors with the active metal electrode. For example, a Li_3N layer may be formed on a Li anode by contacting Cu_3N with the Li anode surface, or Li_3P may be formed on a Li anode by contacting red phosphorus with the Li anode surface.

The invention encompasses protected anode structures with fully-formed protective layers and battery separators incorporating ambient stable precursors, each of which may be handled or stored in normal ambient atmospheric conditions without degradation prior to incorporation into a battery cell. Battery cells and methods for making composites and battery cells are also provided.

These and other features of the invention are further described and exemplified in the detailed description below.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic illustration of an active metal battery cell incorporating an ionically conductive protective membrane in accordance with the present invention.

Figs. 2A and B are a schematic illustrations of ionically conductive protective membrane battery separators in accordance with the present invention.

Fig. 3A is a schematic illustration of an active metal anode structure incorporating an ionically conductive protective laminate composite membrane in accordance with the present invention.

Fig. 3B is a schematic illustration of an active metal anode structure incorporating an ionically conductive protective graded composite membrane in accordance with the present invention.

Figs. 4A-B, 5 and 6A-B are schematic illustrations of alternative methods of making an electrochemical device structure incorporating an ionically conductive protective membrane in accordance with the present invention.

Figs. 7A-B and 8A-D are plots of data illustrating the performance benefits of ionically conductive protective membranes in accordance with the present invention.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Reference will now be made in detail to specific embodiments of the invention. Examples of the specific embodiments are illustrated in the accompanying drawings. While the invention will be described in conjunction with these specific embodiments, it will be understood that it is not intended to limit the invention to such specific embodiments. On the contrary, it is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. The present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention.

When used in combination with "comprising," "a method comprising," "a device comprising" or similar language in this specification and the appended claims, the singular forms "a," "an," and "the" include plural reference unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood to one of ordinary skill in the art to which this invention belongs.

Introduction

The present invention provides ionically conductive membranes for decoupling the active metal anode and cathode sides of an active metal electrochemical cell, and methods for their fabrication. The membranes may be incorporated in active metal negative electrode (anode) structures and electrochemical devices and components, including battery and fuel cells. The membranes are highly conductive for ions of the active metal, but are otherwise substantially impervious. They are chemically stable on one side to the active metal of the anode (e.g., lithium), and on the other side to the cathode, other battery cell components such as solid or liquid phase electrolytes, including organic or aqueous liquid electrolytes, and preferably to ambient conditions. The membrane is capable of protecting an active metal anode from deleterious reaction with other battery components or ambient conditions and decoupling the chemical environments of the anode and cathode enabling use of anode-incompatible materials, such as solvents and electrolytes, on the cathode side without deleterious impact on the anode, and vice versa. This broadens the array of materials that may be used in active metal electrochemical cells and facilitates cell fabrication while providing a high level of ionic conductivity to enhance performance of an electrochemical cell in which the membrane is incorporated.

The membrane may have any suitable composition, for example, it may be a monolithic material chemically compatible with both the anode and cathode environments, or a composite composed of at least two components of different materials having different chemical compatibilities, one chemically compatible with the anode environment and the other chemically compatible with the cathode environment.

Composite membranes may be composed of at least two components of different materials having different chemical compatibility requirements. The composite may be composed of a laminate of discrete layers of materials having different chemical compatibility requirements, or it may be composed of a gradual transition between layers of the materials. By "chemical compatibility" (or "chemically compatible") it is meant that the referenced material does not react to form a product that is deleterious to battery cell operation when contacted with one or more other referenced battery cell components or manufacturing, handling or storage conditions.

A first material layer of the composite is both ionically conductive and chemically compatible with an active metal electrode material. Chemical compatibility in this aspect of the invention refers to a material that is chemically stable and therefore substantially unreactive when contacted with an active metal electrode material. Active metals are highly reactive in ambient conditions and can benefit from a barrier layer when used as electrodes. They are generally alkali metals such (e.g., lithium, sodium or potassium), alkaline earth metals (e.g., calcium or magnesium), and/or certain transitional metals (e.g., zinc), and/or alloys of two or more of these. The following active metals may be used: alkali metals (e.g., Li, Na, K), alkaline earth metals (e.g., Ca, Mg, Ba), or binary or ternary alkali metal alloys with Ca, Mg, Sn, Ag, Zn, Bi, Al, Cd, Ga, In. Preferred alloys include lithium aluminum alloys, lithium silicon alloys, lithium tin alloys, lithium silver alloys, and sodium lead alloys (e.g., Na_4Pb). A preferred active metal electrode is composed of lithium. Chemical compatibility also refers to a material that may be chemically stable with oxidizing materials and reactive when contacted with an active metal electrode material to produce a product that is chemically stable against the active metal electrode material and has the desirable ionic conductivity (i.e., a first layer material). Such a reactive material is sometimes referred to as a "precursor" material.

A second material layer of the composite is substantially impervious, ionically conductive and chemically compatible with the first material. By substantially impervious it is meant that the material provides a sufficient barrier to battery electrolytes and solvents and other battery component materials that would be damaging to the electrode material to prevent any such damage that would degrade electrode performance from occurring. Thus, it should be non-swellable and free of pores, defects, and any pathways allowing air, moisture, electrolyte, etc. to penetrate though it to the first material. Preferably, the second material layer is so impervious to ambient moisture, carbon dioxide, oxygen, etc. that an encapsulated lithium alloy electrode can be handled under ambient conditions without the need for elaborate dry box conditions as typically employed to process other lithium electrodes. Because the composite protective layer described herein provides such good protection for the lithium (or other active metal), it is contemplated that electrodes and electrode/electrolyte composites of this invention may have a quite long shelf life outside of a battery. Thus, the invention contemplates not only batteries containing a negative electrode, but unused negative electrodes and electrode/electrolyte laminates themselves. Such negative electrodes and electrode/electrolyte laminates may be provided in the form of sheets, rolls, stacks, etc. Ultimately, they may be integrated with other battery components to fabricate a battery. The enhanced stability of the batteries of this invention will greatly simplify this fabrication procedure.

In addition to the protective composite laminate structure described above, a protective composite in accordance with the present invention may alternatively be a functionally graded layer, as further described below.

It should be noted that the first and second materials are inherently ionically conductive. That is, they do not depend on the presence of a liquid electrolyte or other agent for their ionically conductive properties.

Additional layers are possible to achieve these aims, or otherwise enhance electrode stability or performance. All layers of the composite have high ionic conductivity, at least 10^{-7}S/cm, generally at least 10^{-6}S/cm, for example at least 10^{-5}S/cm to 10^{-4}S/cm, and as high as 10^{-3}S/cm or higher so that the overall ionic conductivity of the multi-layer protective structure is at least 10^{-7}S/cm and as high as 10^{-3}S/cm or higher.

Protective Membranes and Structures

Fig. 1 illustrates an ionically conductive protective membrane in accordance with the present invention in context as it would be used in an active metal battery cell 120, such as a lithium-sulfur battery, in accordance with the present invention. The membrane 100 is both ionically conductive and chemically compatible with an active metal (e.g., lithium) electrode (anode) 106 on one side, and substantially impervious, ionically conductive and chemically compatible with an electrolyte 110 and/or cathode 112 on the other side. The ionic conductivity of the membrane is at least 10^{-7}S/cm, generally at least 10^{-6}S/cm, for example at least 10^{-5}S/cm to 10^{-4}S/cm, and as high as 10^{-3}S/cm or higher. The active metal anode 106 in contact with the first side of the protective membrane is connected with a current collector 108 composed of a conductive metal, such as copper, that is generally inert to and does not alloy with the active metal. The other side of the membrane 100, is (optionally) in contact with an electrolyte 110. Alternatively, in some embodiments, the protective membrane 100 may itself be the sole electrolyte of the battery cell. Adjacent to the electrolyte is the cathode 112 with its current collector 114.

The protective membrane may be a composite composed of two or more materials that present sides having different chemical compatibility to the anode and electrolyte and/or cathode, respectively. The composite is composed of a first layer of a material that is both ionically conductive and chemically compatible with an active metal electrode material. The composite also includes second layer of a material that is substantially impervious, ionically conductive and chemically compatible with the first material and the cathode/electrolyte environment.

As described further below, given the protection afforded by the protective membranes of the present invention, the electrolytes and/or cathodes combined with the protected anodes of the present invention may include a wide variety of materials including, but not limited to, those described in the patents of PolyPlus Battery Company, referenced herein below.

Fig. 2A illustrates a protective membrane composite battery separator in accordance with one embodiment of the present invention. The separator 200 includes a laminate of discrete layers of materials with different chemical compatibilities. A layer of a first material or precursor 202 is ionically conductive and chemically compatible with an active metal. In most cases, the first material is not chemically compatible with oxidizing materials (e.g., air, moisture, etc). The first layer, in contact with the active metal, may be composed, in whole or in part, of active metal nitrides, active metal phosphides, active metal halides or active metal phosphorus oxynitride-based glasses. Specific examples include Li_3N, Li_3P, LiI, LiBr, LiCl and LiF. In at least one instance, LiPON, the first material is chemically compatible with oxidizing materials. The thickness of the first material layer is preferably about 0.1 to 5 microns, or 0.2 to 1 micron, for example about 0.25 micron.

As noted above, the first material may also be a precursor material which is chemically compatible with an active metal and reactive when contacted with an active metal electrode material to produce a product that is chemically stable against the active metal electrode material and has the desirable ionic conductivity (i.e., a first layer material). Examples of suitable precursor materials include metal nitrides, red phosphorus, nitrogen and phosphorus containing organics (e.g., amines, phosphines, borazine ($B_3N_3H_6$), triazine ($C_3N_3H_3$)) and halides. Some specific examples include P (red phosphorus), Cu_3N, SnN_x, Zn_3N_2, FeN_x, CoN_x, aluminum nitride (AlN), silicon nitride (Si_3N_4) and I_2, Br_2, Cl_2 and F_2. Such precursor materials can subsequently react with active metal (e.g., Li) to form a Li metal salts, such as the lithium nitrides, phosphides and halides described above. In some instances, these first layer material precursors may also be chemically stable in air (including moisture and other materials normally present in ambient atmosphere), thus facilitating handling and fabrication. Examples include metal nitrides, for example Cu_3N.

Also, a suitable active metal compatible layer may include a polymer component to enhance its properties. For example, polymer-iodine complexes like poly(2-vinylpyridine)-iodine ($P2VP-I_2$), polyethylene-iodine, or with tetraalkylammonium-iodine complexes can react with Li to form a LiI-based film having significantly higher ionic conductivity than that for pure LiI.

The ionic conductivity of the first material is high, at least 10^{-7} S/cm, generally at least about 10^{-5} S/cm, and may be as high as 10^{-3} S/cm or higher.

Adjacent to the first material or precursor layer 202 is a second layer 204 that is substantially impervious, ionically conductive and chemically compatible with the first material or precursor, including glassy or amorphous metal ion conductors, such as a phosphorus-based glass, oxide-based glass, phosphorus-oxynitride-based glass, sulpher-based glass, oxide/sulfide based glass, selenide based glass, gallium based glass, germanium-based glass or boracite glass (such as are described D.P. Button et al., Solid State Ionics, Vols. 9-10, Part 1, 585-592 (December 1983); ceramic active metal ion conductors, such as lithium beta-alumina, sodium beta-alumina, Li superionic conductor (LISICON), Na superionic conductor (NASICON), and the like; or glass-ceramic active metal ion conductors. Specific examples include LiPON, $Li_3PO_4.Li_2S.SiS_2$, $Li_2S.GeS_2.Ga_2S_3$, $Li_2O{\cdot}11Al_2O_3$, $Na_2O{\cdot}11Al_2O_3$, $(Na, Li)_{1+x}Ti_{2-x}Al_x(PO_4)_3$ ($0.6 \leq x \leq 0.9$) and crystallographically related structures, $Na_3Zr_2Si_2PO_{12}$, $Li_3Zr_2Si_2PO_{12}$, $Na_5ZrP_3O_{12}$, $Na_5TiP_3O_{12}$, $Na_3Fe_2P_3O_{12}$, $Na_4NbP_3O_{12}$, $Li_5ZrP_3O_{12}$, $Li_5TiP_3O_{12}$, $Li_3Fe_2P_3O_{12}$ and $Li_4NbP_3O_{12}$, and combinations thereof, optionally sintered or melted. Suitable ceramic ion active metal ion conductors are described, for example, in US Patent No. 4,985,317 to Adachi *et al.*, incorporated by reference herein in its entirety and for all purposes.

A particularly suitable glass-ceramic material for the second layer of the protective composite is a lithium ion conductive glass-ceramic having the following composition:

Composition	mol %
P_2O_5	26-55%

SiO_2	0-15%
$GeO_2 + TiO_2$	25-50%
in which GeO_2	0--50%
TiO_2	0--50%
ZrO_2	0-10%
M_2O_3	0 < 10%
Al_2O_3	0-15%
Ga_2O_3	0-15%
Li_2O	3-25%

and containing a predominant crystalline phase composed of $Li_{1+x}(M,Al,Ga)_x(Ge_{1-y}Ti_y)_{2-x}(PO_4)_3$ where $X \leq 0.8$ and $0 \leq Y \leq 1.0$, and where M is an element selected from the group consisting of Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb and/or and $Li_{1+x+y}Q_xTi_{2-x}Si_yP_{3-y}O_{12}$ where $0 < X \leq 0.4$ and $0 < Y \leq 0.6$, and where Q is Al or Ga. The glass-ceramics are obtained by melting raw materials to a melt, casting the melt to a glass and subjecting the glass to a heat treatment. Such materials are available from OHARA Corporation, Japan and are further described in US Patent Nos. 5,702,995, 6,030,909, 6,315,881 and 6,485,622, incorporated herein by reference.

The high conductivity of some of these glasses, ceramics and glass-ceramics (ionic conductivity in the range of about 10^{-5} to 10^{-3} S/cm or greater) may enhance performance of the protected lithium anode, and allow relatively thick films to be deposited without a large penalty in terms of ohmic resistance.

Also, for solid state applications, a suitable second layer may include a polymer component to enhance its properties. For example, a glass-ceramic active metal ion conductor, like the glass-ceramic materials described above, may also be combined with polymer electrolytes to form flexible composite sheets of material which may be used as second layer of the protective composite. One important example of such a flexible composite material has been developed by OHARA Corp. (Japan). It is composed of particles of a Li-ion conducting glass-ceramic material, such as described above, and a solid polymer electrolyte based on PEO-Li salt complexes. OHARA Corp. manufactures this material in the form of sheet with a thickness of about 50 microns that renders it flexible while maintaining its high ionic conductivity. Because of its relatively high ionic conductivity (better than $4*10^{-5}$ S/cm at room temperature in the case of the OHARA product) and stability toward metallic Li, this type of composite electrolyte can be used at room temperature or elevated temperatures in fully solid-state cells.

The composite barrier layer should have an inherently high ionic conductivity. In general, the ionic conductivity of the composite is at least 10^{-7} S/cm, generally at least about 10^{-6} to 10^{-5} S/cm, and may be as high as 10^{-4} to 10^{-3} S/cm or higher. The thickness of the first precursor material layer should be enough to prevent contact between the second material layer and adjacent materials or layers, in particular, the active metal of the anode with which the separator is to be used. For example, the first material layer may have a thickness of about 0.1 to 5 microns; 0.2 to 1 micron; or about 0.25 micron.

The thickness of the second material layer is preferably about 0.1 to 1000 microns, or, where the ionic conductivity of the second material layer is about 10^{-7} S/cm, about 0.25 to 1 micron, or, where the ionic conductivity of the second material layer is between about 10^{-4} about 10^{-3} S/cm, about 10 to 1000 microns, preferably between 1 and 500 microns, and more preferably between 10 and 100 microns, for example 20 microns.

When the first material layer is a precursor material chemically stable in air, for example Cu_3N or LiPON, the protective composite battery separator may be handled or stored in normal ambient atmospheric conditions without degradation prior to incorporation into a battery cell. When the separator is incorporated into a battery cell, the precursor layer 202 is contacted with an active metal (e.g., lithium) electrode. The precursor reacts with the active metal to form an ionically conductive material that is chemically compatible with the active metal electrode material. The second layer is contacted with an electrolyte to which a cathode and current collector is or has been applied. Alternatively, the second layer acts as the sole electrolyte in the battery cell. In either case, the combination of the two layers in the protective composite protects the active metal electrode and the electrolyte and/or cathode from deleterious reaction with one another.

In addition to the protective composite laminates described above, a protective composite in accordance with the present invention may alternatively be compositionally and functionally graded, as illustrated in Fig. 2B. Through the use of appropriate deposition technology such as RF sputter deposition, electron beam deposition, thermal spray deposition, and or plasma spray deposition, it is possible to use multiple sources to lay down a graded film. In this way, the discrete interface between layers of distinct composition and functional character is replaced by a gradual transition of from one layer to the other. The result, as with the discrete layer composites described above, is a bi-functionally compatible ionically conductive composite 220 stable on one side 214 to lithium or other active metal (first material), and on the other side 216 substantially impervious and stable to ambient conditions, and ultimately, when incorporated into a battery cell, to the cathode, other battery cell components (second material). In this embodiment, the proportion of the first material to the second material in the composite may vary widely based on ionic conductivity and mechanical strength issues, for example. In many, but not all, embodiments the second material will dominate. For example, suitable ratios of first to second materials may be 1-1000 or 1-500, for example about 1 to 200 where the second material has greater strength and ionic conductivity than the first (e.g., 2000Å of LiPON and 20-30microns of OHARA glass-ceramic). The transition between materials may occur over any (e.g., relatively short, long or intermediate) distance in the composite. Other aspects of the invention apply to these graded protective composites substantially as to the discrete-layered laminate protective composites, for example, they may be used in the electrode and cell embodiments, etc.

Fig. 3A illustrates an encapsulated anode structure incorporating a protective laminate composite in accordance with the present invention. The structure 300 includes an active metal electrode 308, e.g., lithium, bonded with a current collector 310, e.g., copper, and a protective composite 302. The protective composite 302 is composed of a first layer 304 of a material that is both ionically conductive and chemically compatible with an active metal electrode material, but not chemically compatible with oxidizing materials (e.g., air). For example, the first layer, in contact with the active metal, may be composed, in whole or in part, of active metal nitrides, active metal phosphides or active metal halides. Specific examples include Li_3N, Li_3P, LiI, LiBr, LiCl and LiF. The thickness of the first material layer is preferably about 0.1 to 5 microns, or 0.2 to 1 micron, for example about 0.25 micron.

Active metal electrode materials (e.g., lithium) may be applied to these materials, or they may be formed *in situ* by contacting precursors such as metal nitrides, metal phosphides, metal halides, red phosphorus, iodine and the like with lithium. The *in situ* formation of the first layer may be by way of conversion of the precursors to a lithiated analog, for example, according to reactions of the following type (using P, CuN_3, and PbI_2 precursors as examples):

1. $3Li + P = Li_3P$ (reaction of the precursor to form Li-ion conductor);

2(a). $3Li + Cu_3N = Li_3N + 3\ Cu$ (reaction to form Li-ion conductor/metal composite);

2(b). $2Li + PbI_2 = 2\ LiI + Pb$ (reaction to form Li-ion conductor/metal composite).

First layer composites, which may include electronically conductive metal particles, formed as a result of *in situ* conversions meet the requirements of a first layer material for a protective composite in accordance with the present invention and are therefore within the scope of the invention.

A second layer 306 of the protective composite is composed of a substantially impervious, ionically conductive and chemically compatible with the first material or precursor, including glassy or amorphous metal ion conductors, such as a phosphorus-based glass, oxide-based glass, phosphorus-oxynitride-based glass, sulpher-based glass, oxide/sulfide based glass, selenide based glass, gallium based glass, germanium-based glass or boracite glass; ceramic active metal ion conductors, such as lithium beta-alumina, sodium beta-alumina, Li superionic conductor (LISICON), Na superionic conductor (NASICON), and the like; or glass-ceramic active metal ion conductors. Specific examples include LiPON, $Li_3PO_4.Li_2S.SiS_2$, $Li_2S.GeS_2.Ga_2S_3$, $Li_2O{\cdot}11Al_2O_3$, $Na_2O{\cdot}11Al_2O_3$, $(Na, Li)_{1+x}Ti_{2-x}Al_x(PO_4)_3$ ($0.6 \leq x \leq 0.9$) and crystallographically related structures, $Na_3Zr_2Si_2PO_{12}$, $Li_3Zr_2Si_2PO_{12}$, $Na_5ZrP_3O_{12}$, $Na_5TiP_3O_{12}$, $Na_3Fe_2P_3O_{12}$, $Na_4NbP_3O_{12}$, $Li_5ZrP_3O_{12}$, $Li_5TiP_3O_{12}$, $Li_3Fe_2P_3O_{12}$ and

$Li_4NbP_3O_{12}$, and combinations thereof, optionally sintered or melted. Suitable ceramic ion active metal ion conductors are described, for example, in US Patent No. 4,985,317 to Adachi *et al.*, incorporated by reference herein in its entirety and for all purposes. Suitable glass-ceramic ion active metal ion conductors are described, for example, in US Patents Nos. 5,702,995, 6,030,909, 6,315,881 and 6,485,622, previously incorporated herein by reference and are available from OHARA Corporation, Japan.

The ionic conductivity of the composite is at least 10^{-7}S/cm, generally at least 10^{-6}S/cm, for example at least 10^{-5}S/cm to 10^{-4}S/cm, and as high as 10^{-3}S/cm or higher. The thickness of the second material layer is preferably about 0.1 to 1000 microns, or, where the ionic conductivity of the second material layer is about 10^{-7} S/cm, about 0.25 to 1 micron, or, where the ionic conductivity of the second material layer is between about 10^{-4} about 10^{-3} S/cm, 10 to 1000 microns, preferably between 1 and 500 micron, and more preferably between 10 and 100 microns, for example 20 microns.

When the anode structure is incorporated in a battery cell, the first layer 304 is adjacent to an active metal (e.g., lithium) anode and the second layer 306 is adjacent to an electrolyte or, where the second layer is the sole electrolyte in the battery cell, a cathode.

Either layer may also include additional components. For instance, a suitable first active metal compatible layer 304 may include a polymer component to enhance its properties. For example, polymer-iodine complexes like poly(2-vinylpyridine)-iodine ($P2VP-I_2$), polyethylene-iodine, or with tetraalkylammonium-iodine can react with Li to form a LiI-based film having significantly higher ionic conductivity than that for pure LiI. Also, for solid state applications, a suitable second layer 306 may include a polymer component to enhance its properties. For example, a glass-ceramic active metal ion conductor like that available from OHARA Corporation, described above, may be fabricated within a polymer matrix that renders it flexible while maintaining its high ionic conductivity (available from OHARA Corporation, Japan).

In addition, the layers may be formed using a variety of techniques. These include deposition or evaporation (including e-beam evaporation) of layers of material, such as LiN_3 or an ionically conductive glass. Also, as noted above, the active metal electrode adjacent layer may be formed *in situ* from the non-deleterious reaction of one or more precursors with the active metal electrode. For example, a LiN_3 layer may be formed on a Li anode by contacting CuN_3 with the Li anode surface, or LiP_3 may be formed on a Li anode by contacting red phosphorus with the Li anode surface.

As noted above with regard to the protective membrane separator structures described in connection with Figs. 2A and B, in addition to the protective composite laminates described above, a protective composite in accordance with the present invention may alternatively be compositionally and functionally graded, as illustrated in Fig. 3B. Through the use of appropriate deposition technology such as RF sputter deposition, electron beam deposition, thermal spray deposition, and or plasma spray deposition, it is possible to use multiple sources to lay down a graded film. In this way, the discrete interface between layers of distinct composition and functional character is replaced by a gradual transition of from one layer to the other. The result, as with the discrete layer composites described above, is a bi-functionally compatible ionically conductive composite 320 stable on one side 314 to lithium or other active metal (first material), and on the other side 316 substantially impervious and stable to the cathode, other battery cell components and preferably to ambient conditions (second material).

As noted with reference to the graded separator in Fig. 2B, in this embodiment the proportion of the first material to the second material in the composite may vary widely based on ionic conductivity and mechanical strength issues, for example. In many, but not all, embodiments the second material will dominate. For example, suitable ratios of first to second materials may be 1-1000 or 1-500, for example about 1 to 200 where the second material has greater strength and ionic conductivity than the first (e.g., 2000Å of LiPON and 20-30microns of OHARA glass-ceramic). The transition between materials may occur over any (e.g., relatively short, long or intermediate) distance in the composite.

Also, an approach may be used where a first material and second material are coated with another material such as a transient and/or wetting layer. For example, an OHARA glass ceramic plate is coated with a LiPON layer, followed by a thin silver (Ag) coating. When lithium is evaporated onto this structure, the Ag is converted to

Ag-Li and diffuses, at least in part, into the greater mass of deposited lithium, and a protected lithium electrode is created. The thin Ag coating prevents the hot (vapor phase) lithium from contacting and adversely reaction with the LiPON first material layer. After deposition, the solid phase lithium is stable against the LiPON. A multitude of such transient/wetting (e.g., Sn) and first layer material combinations can be used to achieve the desired result.

Thus, the invention encompasses protected anode structures with fully-formed protective layers and battery separators incorporating ambient stable precursors, each of which may be handled or stored in normal ambient atmospheric conditions without degradation prior to incorporation into a battery cell. Battery cells and methods for making separators, anode structures and battery cells are also provided.

Battery Cells

Protected active metal anodes as described herein may be incorporated into a variety of battery cell structures. These includes fully solid state battery cells and battery cells with gel and liquid electrolyte systems, including, but not limited to, those described in the patents of PolyPlus Battery Company, referenced herein.

Solid and Gel State Batteries

A solid state battery cell in accordance with the present invention may include a protected anode as described herein against a polymer electrolyte such as polyethylene oxide (PEO), and a PEO/carbon/metal-oxide type cathode.

Alternatively, gel-state electrolytes in which non-aqueous solvents have been gelled through the use of a gelling agent such as polyacrylonitrile (PAN), polyethylene oxide (PEO), polyvinylidene fluoride (PVDF), or polymerizable monomers that are added to the non-aqueous solvent system and polymerized *in situ* by the use of heat or radiation may be used.

Examples of suitable solid and gel state electrolytes and batteries incorporating them are described, for example, in US Patent No. 6,376,123, issued April 23, 2002 and titled RECHARGEABLE POSITIVE ELECTRODES, assigned to PolyPlus Battery Company, the assignee of the present application, which is incorporated herein by reference in its entirety and for all purposes.

Liquid Electrolytes

One of the main requirements of the liquid electrolyte system for all Li-metal and Li-ion battery cells is its compatibility with the anode material. The liquid electrolytes of existing Li-metal and Li-ion cells are not thermodynamically stable toward Li metal, Li alloys, and Li-C compounds, but rather kinetically stable due to formation of a solid electrolyte interface (SEI) protecting the anode surface from a continuous reaction with components of the electrolyte. Therefore, only a very limited spectrum of aprotic solvents and supporting salts is suitable for use in Li-metal and Li-ion batteries with an unprotected anode. In particular, the binary, ternary or multicomponent mixtures of alkyl carbonates or their mixtures with ethers are used as solvents, and $LiPF_6$ is generally used as a supporting salt in electrolytes for Li-ion batteries.

The main component of these solvent mixtures is ethylene carbonate (EC). It has been shown that without the presence of EC in the electrolyte, the SEI formed does not provide enough protection for anode surface, and cell's cyclability is very poor. However, EC has a high melting point of 35°C and a high viscosity that limits the rate capability and the cell's low temperature performance. Another important disadvantage of existing Li-ion batteries is the irreversible capacity loss during the first charge associated with *in situ* formation of the SEI.

Protection of the anode with an ionically conductive protective membrane in accordance with the present invention allows for use of a very wide spectrum of solvents and supporting salts in rechargeable and primary batteries with Li metal anodes. The protected anode is completely decoupled from the electrolyte, so electrolyte compatibility with the anode is no longer an issue; solvents and salts which are not kinetically stable to Li can be used. Improved performance can be obtained with conventional liquid electrolytes, as noted above and as described, for example, in US Patent No. 6,376,123, previously incorporated herein by reference. Moreover, the electrolyte solution can be composed of only low viscosity solvents, such as ethers like 1,2-dimethoxy ethane (DME), tetrahydrofuran (THF), 2-methyltetrahydrofuran, 1,3-dioxolane (DIOX), 4-methyldioxolane (4-MeDIOX) or organic carbonates like dimethylcarbonate (DMC), ethylmethylcarbonate (EMC), diethylcarbonate (DEC), or their mixtures. Also, super low viscosity ester solvents or co-solvents such as methyl formate and methyl acetate, which are very reactive to unprotected Li, can be used. As is known to those skilled in the art, ionic conductivity and diffusion rates are inversely proportional to viscosity such that all other things being equal, battery performance improves as the viscosity of the solvent decreases. The use of such electrolyte solvent systems significantly improves battery performance, in particular discharge and charge characteristics at low temperatures.

Ionic Liquids

Ionic liquids are organic salts with melting points under 100 degrees, often even lower than room temperature. The most common ionic liquids are imidazolium and pyridinium derivatives, but also phosphonium or tetralkylammonium compounds are also known. Ionic liquids have the desirable attributes of high ionic conductivity, high thermal stability, no measurable vapor pressure, and non-flammability. Representative ionic liquids are 1-Ethyl-3-methylimidazolium tosylate (EMIM-Ts), 1-Butyl-3-methylimidazolium octyl sulfate (BMIM-OctSO4), 1-Ethyl-3-methylimidazolium hexafluorophosphate, and 1-Hexyl-3-methylimidazolium tetrafluoroborate. Although there has been substantial interest in ionic liquids for electrochemical applications such as capacitors and batteries, they are unstable to metallic lithium and lithiated carbon. However, protected lithium anodes as described in this invention are isolated from direct chemical reaction, and consequently lithium metal batteries using ionic liquids can be developed as an embodiment of the present invention. Such batteries should be particularly stable at elevated temperatures.

Cathodes

Another important advantage associated with the use of ionically conductive protective membranes in accordance with the present invention in battery cells is that both lithiated intercalation compounds and unlithiated intercalation compounds can be used as cathode materials. As a result, protection of the anode with ionically conductive composite materials allows for use of a variety of 2, 3, 4 and 5 V cathodes suitable for fabrication of primary and rechargeable batteries for a wide range of applications. Examples of lithiated metal oxide based cathodes suitable for rechargeable cells with protected Li anodes in accordance with the present invention include: Li_xCoO_2, Li_xNiO_2, $Li_xMn_2O_4$ and $LiFePO_4$. Examples of unlithiated metal oxide or sulfide based cathodes suitable for use both for primary and rechargeable cells with protected Li anodes in accordance with the present invention include: $AgxV_2O_5$, $CuxV_2O_5$, V_2O_5, V_6O_{13}, FeS_2 and TiS_2. Examples of metal oxide based cathodes suitable for primary cells with protected Li anodes in accordance with the present invention include: MnO_2, CuO, Ag_2CrO_4 and MoO_3. Examples of metal sulfide based positive electrodes for primary cells with protected Li anodes in accordance with the present invention include: CuS and FeS.

In addition, active sulfur cathodes including elemental sulfur and polysulfides, as described in the patents of PolyPlus Battery Company cited and incorporated by reference below are suitable cathodes for protected lithium metal anode battery cells in accordance with the present invention.

Fabrication Techniques

Materials and techniques for fabrication of active metal battery cells are described, for example, in US Patents Nos. 5,686,201and 6,376,123 issued to Chu on November 11, 1997. Further description of materials and techniques for fabrication of active metal battery cells having anode protective layers are described, for example, in U.S. Patent Application No. 09/139,601, filed August 25, 1998 (now U.S. Patent No. 6,214,061, issued April 10, 2001), titled ENCAPSULATED LITHIUM ALLOY ELECTRODES HAVING BARRIER LAYERS, and naming May-Ying Chu, Steven J. Visco and Lutgard C. DeJonge as inventors; U.S. Patent Application No. 09/086,665 filed May 29, 1998 (now U.S. Patent No. 6,025,094, issued May 15, 2000), titled PROTECTIVE COATINGS FOR NEGATIVE ELECTRODES, and naming Steven J. Visco and May-Ying Chu as inventors; U.S. Patent Application No. 09/139,603 filed August 25, 1998 (now U.S. Patent No. 6,402,795, issued June 11, 2002), titled "PLATING METAL NEGATIVE ELECTRODES UNDER PROTECTIVE COATINGS," and naming May-Ying Chu, Steven J. Visco and Lutgard C. DeJonghe as inventors; U.S. Patent Application No. 09/139,601 filed August 25, 1998 (now U.S. Patent No. 6,214,061, issued April 10, 2001), titled "METHOD FOR FORMING ENCAPSULATED LITHIUM ELECTRODES HAVING GLASS PROTECTIVE LAYERS," and naming Steven J. Visco and Floris Y. Tsang as inventors. The active metal electrode may also be an active metal alloy electrode, as further described in U.S. Patent Application No. 10/189,908 filed July 3, 2002, titled "ENCAPSULATED ALLOY ELECTRODES," and naming Steven J. Visco, Yevgeniy S. Nimon and Bruce D. Katz as inventors. The battery component materials, including anodes, cathodes, separators, protective layers, etc., and techniques disclosed therein are generally applicable to the present invention and each of these patent applications is incorporated herein by reference in its entirety for all purposes.

In particular, a protective membrane in accordance with the present invention may be formed using a variety of methods. These include deposition or evaporation. Protective membrane composites of the present invention may be formed by deposition or evaporation (including e-beam evaporation) of the first layer of material or precursor on the second layer of material. Also, as noted above and described further below, the first layer may be formed *in situ* from the non-deleterious reaction of one or more precursors with an active metal electrode or material, by deposition or evaporation of lithium on the precursor, by direct contact of the precursor with a lithium metal (e.g., foil), or by plating of the precursor with lithium through a second layer material. In some embodiments, the second layer material may also be formed on the first layer material, as described further below.

Referring to Fig. 4A, a first method for forming a protective membrane composite in accordance with the present invention is shown. A first layer, that is a highly ionically conductive active metal chemically compatible material, is directly deposited onto a second layer material, that is a substantially impervious, ionically conductive material, for example, a highly ionically conductive glass or glass-ceramic material such as LiPON or an OHARA glass-ceramic material described above. This can be done by a variety of techniques including RF sputtering, e-beam evaporation, thermal evaporation, or reactive thermal or e-beam evaporation, for example. In the particular example illustrated in the figure, lithium is evaporated in a nitrogen plasma to form a lithium nitride (Li_3N) layer on the surface of a glass-ceramic material such as the OHARA material described above. This is followed by evaporation of lithium metal onto the Li_3N film. The Li_3N layer separates the lithium metal electrode from the second material layer, but allows Li ions to pass from the Li electrode through the glass. Of course, other active metal, and first and second layer materials, as described herein, may be used as well.

Alternatively, referring to Fig. 4B, a second method for forming a protective membrane composite in accordance with the present invention is shown. The ionically conductive chemically compatible first layer material is formed *in situ* following formation of a precursor layer on the second layer material. In the particular example illustrated in the figure, a surface of a glass-ceramic layer, for example one composed of the OHARA material described above, is coated with red phosphorus, a precursor for an active metal (in this case lithium) phosphide. Then a layer of lithium metal is deposited onto the phosphorus. The reaction of lithium and phosphorus forms Li_3P according to the following reaction: $3Li + P = Li_3P$. Li_3P is an ionically conductive material that is chemically compatible with both the lithium anode and the glass-ceramic material. In this way, the glass-ceramic (or other second layer material) is not in direct contact with the lithium electrode. Of course, other active metal, first layer precursor and second layer materials, as described herein, may be used as well. Alternative precursor examples include CuN_3, which may be formed as a thin layer on a second layer material (e.g., glass-ceramic) and contacted with a Li anode in a similar manner according to the following reaction: $3Li + Cu_3N = Li_3N + 3 Cu$; or lead iodide which may be formed as a thin layer on a polymer electrolyte and contacted with a Li anode in a similar manner according to the following reaction: $2Li + PbI_2 = 2 LiI + Pb$.

In another alternative, illustrated in Fig. 5, a protective membrane composite in accordance with the present invention may alternatively be compositionally and functionally graded so that there is a gradual transition of from one layer to the other. For example, a plasma spray operation with two spray heads, one for the deposition of a first component material, such as Li_3N, Cu_3N, Li_3P, LiPON, or other appropriate material, and the other for the deposition of a second component material, such as an OHARA glass-ceramic, may be used. The first plasma spray process begins laying down a layer of pure glass-ceramic material, followed by a gradual decrease in flow as the second plasma spray torch is gradually turned on, such that there is a gradient from pure glass-ceramic to a continuous transition from glass-ceramic to pure LiPON or Li_3N, etc. In this way, one side of the membrane is stable to active metal (e.g., lithium, sodium, etc.) and the other side is substantially impervious and stable to the cathode, other battery cell components and preferably to ambient conditions. Electron beam deposition or thermal spray deposition may also be used. Given the parameters described herein, one or skill in the art will be able to use any of these techniques to form the graded composites of the invention.

To form a protected anode, lithium is then bonded to the graded membrane on the first layer material (stable to active metal) side of the graded protective composite, for example by evaporation of lithium onto the protective composite as described above. It may also be desirable to add a bonding layer on top of the lithium stable side of the graded composite protective layer, such as Sn, Ag, Al, etc., before applying lithium.

In any of the forgoing methods described with reference to Figs. 4A-B and 5, rather than forming a lithium (or other active metal) layer on the first layer material or precursor, the first layer material or precursor of the protective composite may be contacted with the lithium by bonding metallic lithium to the protective interlayer material or precursor, for example by direct contact with extruded lithium metal foil.

In a further embodiment, a suitable substrate, e.g., having a wetting layer, such as a film of tin on copper, may be coated with a first layer material precursor, e.g., Cu_3N. This may then be coated with a second layer material, e.g., a (ionically) conductive glass. An active metal electrode may then be formed by plating the tin electrode with lithium (or other active metal), through the first and second layer materials. The Cu_3N precursor is also converted to Li_3N by this operation to complete the protective composite in accordance with the present invention on a lithium metal electrode. Details of an active metal plating process are described in commonly assigned US Patent No. 6,402,795, previously incorporated by reference.

With regard to the fabrication methods described above it is important to note that commercial lithium foils are typically extruded and have numerous surface defects due to this process, many of which have deep recesses that would be unreachable by line-of-sight deposition techniques such as RF sputter deposition, thermal and E-beam evaporation, etc. Another issue is that active metals such as lithium may be reactive to the thin-film deposition environment leading to further deterioration of the surface during the coating process. This typically leads to gaps and holes in a membrane deposited onto the surface of an active metal electrode.

However, by inverting the process, this problem is avoided; lithium is deposited on the protective membrane rather than the protective membrane being deposited on lithium. Glass, and glass-ceramic membranes can be made quite smooth either by melt-casting techniques, cut and polish methods, or a variety of known methods leading to smooth surfaces (lithium is a soft metal that cannot be polished). Single or multiple smooth, gap-free membranes may then be deposited onto the smooth surface. After deposition is complete, active metal can be deposited onto the smooth surface by evaporation, resulting is a active meta/protective membrane interface that is smooth and gap-free. Alternatively, a transient bonding layer such as Ag can be deposited onto the protective membrane such that extruded lithium foil can be joined to the membrane by pressing the foil against the Ag layer.

Also as noted above, in an alternative embodiment of the invention the first layer may include additional components. For instance, a suitable first layer may include a polymer component to enhance its properties. For example, polymer-iodine complexes like poly(2-vinylpyridine)-iodine (P2VP-I_2), polyethylene-iodine, or tetraalkylammonium-iodine can react with Li to form an ionically conductive LiI-based film that is chemically compatible with both an active metal and a second layer material as described herein. Without intending to be bound by theory, it is expected that the use of polymer-iodine charge transfer complexes can lead to formation of composites containing LiI and polymer and having significantly higher ionic conductivity than that for pure LiI. Other halogens may also be used in this manner, for example in bromine complexes.

Referring to Fig. 6A, a first embodiment of this aspect of the present invention is shown. A polymer layer and a layer of iodine are coated on a second layer material surface and allowed to react forming polymer-iodine complex.

According to this method, a thin layer of polymer may be applied to the second material layer (e.g., conductive glass) using brushing, dipping, or spraying. For example, a conductive glass layer may be coated with a thin (e.g., 0.5 to 2.0 micron, preferably 0.1 to 0.5 micron) layer of P2VP in this way.

One technique for applying an iodine coating is sublimation of crystalline iodine that can be achieved at room temperature (e.g., about 20 to 25°C) in a reactor placed in the dry box or in a dry room. A sublimed layer of iodine can be made very thin (e.g., 0.05 to 1.0 microns and the rate of sublimation can be adjusted by varying the temperature or distance between the substrate and source of iodine.

Alternatively, high concentrations (e.g., 50 to 100 g/liter of iodine can be dissolved in an organic solvent, such as acetonitrile and n-heptane. Dissolved iodine can be coated on the conductive glass surface by such methods as dip coating, spraying or brushing, among others. In this case, treatment conditions can be easily changed by varying the length of coating treatment and iodine concentrations. Examples of iodine sources for this technique include metal iodides are AgI and PbI_2, which are known to be used as the cathode materials in solid-state batteries with Li anode and LiI-based solid electrolyte.

Then, lithium (or other active metal) is contacted with the polymer-iodine complex on the conductive glass (or other second layer material), for example by evaporation or pressing onto the glass coated with this complex. The result is a LiI-containing composite protective barrier layer on the Li anode.

Referring to Fig. 6B, an alternative embodiment of this aspect of the present invention is shown. A conductive glass (or other second layer material) surface is coated with a thin layer of iodine, such as by a technique described above, that can react with Li forming LiI layer (A).

Active metal, for example lithium foil, can be coated with a thin layer of polymer (B), for example as described above, and then contacted with the iodine layer on the glass. After assembly, iodine reacts with the polymer layer and, as a result, LiI-containing composite protective barrier layer with reduced impedance is formed.

Examples

The following examples provide details illustrating advantageous properties, in particular very low impedance, of composite membrane protective structures in accordance with the present invention on lithium electrodes. These examples are provided to exemplify and more clearly illustrate aspects of the present invention and are in no way intended to be limiting.

Example 1: Impedance measurements using LIPON in composite protective layer

Approximately 0.75 microns of LiPON was RF sputter-deposited onto copper foil samples in a MRC 8671 Sputter Deposition system. Some of the copper foil samples were coated with an additional layer of Cu_3N (approximately 0.9 microns) by RF Magnetron sputtering of a copper target in a nitrogen environment. One LiPON/Cu sample was transferred to a vacuum evaporator, and approximately 3 to 7 microns of lithium metal was evaporated directly onto the LiPON surface. Another Cu_3N/LiPON/Cu sample was coated with a similar thickness of lithium. The impedance for the unprotected LiPON/Cu sample is shown in Fig. 7A; the evaporation of lithium onto the LiPON surface led to a dramatic rise in the resistance of the sample, which is undesirable for electrochemical devices. The beneficial effects of the protective Cu_3N film is seen in Fig. 7B; the impedance is dramatically lower in this case.

Example 2: Impedance measurements using glass-ceramic active metal ion conductor (OHARA) in composite protective layer

Samples of Li^+ conductive glass-ceramic plates were received from OHARA Corporation. Approximately 3 to 7 microns of lithium was evaporated directly onto the OHARA glass-ceramic plate. The deleterious reaction of lithium with the electrolyte is seen in Fig. 8A; the impedance of the sample is quite large, approximately 40,000 Ωcm^2. A film of Cu_3N (about 0.9 microns thick) was RF Magnetron sputter-deposited onto a second sample of glass-ceramic plate, with subsequent evaporation of about 3 to 7 microns of lithium. The beneficial effect of the Cu_3N film can be seen in Fig. 8B; the impedance of the glass-ceramic is dramatically improved relative to the plate without the Cu_3N film. Superimposition of Figs. 8A and 8B in Fig. 8C further illustrates the dramatic improvement in performance for the Cu_3N protected plate. The ionically conductive nature of the protective film is seen in 8D, where lithium is moved across the Li/Cu_3N/glass interface; this is presumably due to conversion of the ionically insulating Cu_3N film to highly conductive Li_3N + Cu.

Conclusion

Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are many alternative ways of implementing both the process and compositions of the present invention. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein.

All references cited herein are incorporated by reference for all purposes.